

## National Center for Manufacturing Sciences

## Advanced Spindles to Improve Manufacturing Productivity

*Spindles are rotating drive shafts that hold cutting instruments in machine tools. As of 1993, the U.S. auto industry was using machine tools to cut 200 million holes in vehicle components annually. If faster, more powerful, and flexible spindles in machine tools could reduce the number of cuts in manufacturing by half for transmission components alone, machining could be reduced by 100,000 hours, valued at up to \$6 million annually for U.S. auto makers. The National Center for Manufacturing Sciences (NCMS) formed a synergistic consortium of designers, manufacturers, and users to improve spindle technologies by developing new designs for bearings, motors, seals, and shafts, as well as cooling, lubrication, and housing systems. Consortium members were NCMS, Ford Motor Company, General Motors Corporation, Aesop, the Torrington Company, Olofsson Machine Tools Inc., SETCO-Whitnion, Manufacturing Laboratories Inc., ORSCO Inc., and Giddings and Lewis. They applied for cost-shared funding from the Advanced Technology Program (ATP) as a joint-venture project in the 1993 competition. Numerous technical risks included compensating for thermal distortion in bearings, maintaining stiffness in the spindle, and developing long-life bearings that would minimize heat generated during operation.*

*ATP awarded cost-shared funds for a three-year project that began in 1994 and was later extended to 4.5 years. The NCMS-led joint venture developed three prototypes: a heavy-duty 75-horsepower (hp) spindle for cutting large amounts of metal; a more versatile 35-hp spindle for cutting a variety of metals; and a cluster of four spindles (35 hp) to make simultaneous cuts in transmissions and similar parts. The 75-hp spindle accurately bored cylinders and milled flat surfaces with double the metal removal rate of existing machines. The ATP-funded technology earned three technology innovation awards and three patents. Project researchers shared their findings through numerous publications and presentations. After the ATP-funded project ended in 1999, U.S. machine tool manufacturing took a downturn, so the joint-venture partners put the spindle technology on hold. As of 2005, Fisher Electric, a small motor company, is building high-speed motors using the ATP-funded motor technology. Hardinge, which acquired the patents from Aesop, may develop a hydrostatic spindle in the future.*

### COMPOSITE PERFORMANCE SCORE

(based on a four-star rating)

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Research and data for Status Report 93-01-0244 were collected during May – July 2005.

### Spindles Are Key to Machine Tool Performance

Spindles are rotating shafts that serve as axes for cutting tools. These motor-driven shafts both position and transmit power to a tool (such as in the case of milling machines) or hold a rotating workpiece (such as in the case of lathes). As the manufacturing industry becomes increasingly globalized, manufacturers have a strong incentive to improve the productivity of machine

tools through higher speeds, improved power densities, greater flexibility, and more multitasking of operations. These goals require continual innovation and improvement of spindles, because spindles play a key role in the quality of the final product and the overall productivity and efficiency of the machine tool itself.

Spindles hold cutting tools and spin them at high speed and torque (torque is a component of rotational power,

measured in Newton-meters [or foot-pounds]; power [watts or horsepower, hp] is the measure of torque and speed). Spindles support several key machining tasks, such as turning an axle to cut it smoothly, milling the surface of a cylinder head to make it flat, drilling holes, and reaming or enlarging the opening of a hole (with the cutting blades turning like a fan). Bearings hold the spindle steady, preventing vibration or wobbling.

The precision, power, and speed of the spindle strongly influence the part quality and production rates. In the mid-1990s, the U.S. auto industry was cutting 200 million holes in vehicle components each year. Machine time cost \$60 per hour, plus tools, maintenance, and other expenses.

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Manufacturers typically drilled holes at one station and finished them at a second station, fixed transfer lines. A typical auto manufacturing plant had 30 dual-station installations operating 16 hours per day, 220 days per year. Existing high-speed spindles were generally limited to speeds of less than 30,000 revolutions per minute (rpm) due to bearing friction; cutting power was limited to 30 kilowatts (kW). Faster, higher powered spindles could reduce cutting time, as long as they could maintain accuracy. If the number of machining stations required to make transmission components could be cut by half, U. S. auto manufacturers would save more than 100,000 machining hours per year, valued at \$6 million.

As consumers have demanded greater diversity in products, automotive manufacturers have sought more flexible manufacturing processes to produce fewer identical parts with shorter machining runs. This would enable the substitution of flexible machinery for fixed transfer lines. A primary cost of manufacturing is in setting up a production run, so the per-unit setup costs are significantly lower if large volumes of identical components are produced. To cost-effectively produce

a greater variety of smaller runs, manufacturers cut production costs by making more efficient use of the labor involved in setting up and running these small production volumes and by reducing raw material waste by making precision parts right the first time and every time. New spindle technology that had two basic characteristics could meet the need: minimum size and weight and maximum torque over a broad range of speeds. Low weight would allow rapid repositioning of the cutter, and high torque would allow flexibility in cutting a variety of materials while minimizing downtime to change settings.

### **NCMS Proposes High-Performance, More Accurate Spindles**

At the request of Ford Motor Company and General Motors Corporation, the National Center for Manufacturing Sciences (NCMS) formed a synergistic consortium of end users, designers, analysts, and builders to develop innovative spindles that would minimize the size and weight of machine tools while maximizing torque over a range of speeds. The goal was to increase flexibility and efficiency in manufacturing. In addition to NCMS, the joint-venture partners were Ford, General Motors, Aesop, the Torrington Company, Olofsson Machine Tools Inc., SETCO-Whitton, Manufacturing Laboratories Inc., ORSCO Inc., and Giddings and Lewis. The NCMS team proposed to achieve significant technical improvements in spindle technologies by incorporating new concepts and materials in the design of bearings, motors, seals, and shafts, as well as in the cooling, lubrication, and housing systems. These changes were expected to increase spindle speed, power, stiffness, life, productivity, versatility, and maintainability.

Spindle motors available in the 1990s were delivering more power, and available cutting tools could put the increased power to use. The limiting factor was the bearings. The NCMS team chose two types of spindles for further development, distinguished by the bearing used: the rolling-element bearing and the fluid-film bearing. The goal for improving the rolling-element bearing was to develop lightweight, high-performance, integral motor spindles for flexible machining on high-velocity machine tools. The team intended to develop three prototype spindle designs:

- A 35-hp spindle, which covered the power range of 25 to 50 hp over a speed range of 0 to 20,000 rpm using high-speed hybrid ceramic ball bearings
- A 75-hp spindle, which covered the power range of 75 to 100 hp over a speed range of 0 to 12,000 rpm using high-speed tapered-roller bearings
- A cluster spindle to simultaneously cut four closely spaced holes, that used hydrostatic bearings to allow the shafts to be of maximum diameter and stiffness

The goal for the cluster spindle was to develop highly accurate, powerful cluster spindles using pressurized fluid as the lubricant. The NCMS team developed one fluid-film spindle prototype design, the hydrostatic cluster spindle, which is fitted with self-compensated hydrostatic bearings.

Hydrostatic bearings for cluster spindles, with their high load capacity, could overcome performance limits of ball bearings in small spaces between spindle centers by reducing friction. A water-based coolant would be used, not so much as a lubricant, but rather as a means of suspending the bearings completely. In this way, the bearings would not come in contact with any other surface. In addition, this type of bearing was suited to high-speed and high-power machining, because the fluid would keep the spindle cool, deliver smooth motion, damp vibration, and ensure low runout (measurements outside of specifications). Consortium members believed that these factors would prolong the life of the more costly, more shock-sensitive cutting tools that aggressive milling processes are likely to use in cluster drilling, reaming, and tapping applications, such as for manufacturing planet carriers for automatic transmissions.

Numerous high technical risks, which precluded adequate commercial funding, included the following:

- **Thermal distortion.** The NCMS team needed to control thermal distortion, so the high revolutions per minute could be reached without sacrificing bearing life. Hydrostatic bearings used in the 35-hp spindle are water-cooled and not intended for use in high speeds, so thermal distortion would not affect

them. Distortion would be a problem, however, for the rolling-element designs used in the 75-hp spindle. Researchers would use an advanced, electronically controlled lubrication system that would be built by ORSCO and bearings that would be designed by Torrington (later purchased by Timken).

- **Stiffness.** The team needed to develop preloading methods for rolling element supported spindles and a packaging scheme for self-compensated hydrostatic bearings that would permit high stiffness in closely spaced spindles to prevent deflection (droop) at the end of the cluster spindles and maintain precise cutting and hole-center distance.
- **Fabrication procedures.** The team needed to develop low-cost, high-volume fabrication procedures for metal-matrix spindle housings and shafts. The expected complexity of the motor-cooling jacket, new metal-matrix materials for the housing and shaft, and new concepts for constructing permanent-magnet motors would require new fabrication procedures.
- **High-speed motors.** The team needed to develop reliable, low-cost, and high-speed motors and motor controllers for large- and medium-diameter shafts. Spindle weight and heat generation considerations indicated that the researchers should develop a permanent-magnet motor design, which could lead to more efficient and compact motors.
- **High-speed rolling-element bearings.** The team needed to develop high-speed rolling-element bearings and hybrid ceramic bearings with long life and minimum heat generation. To achieve this, it was important to control the dimensional and surface finish quality of the bearings.

ATP awarded cost-shared funding for three years of technical development, beginning in 1994. (The project was later extended to 4.5 years at no additional cost to ATP.) The project goals were to increase the metal removal rate without substantially increasing the cutting forces. Holes and surfaces in engines, transmissions, and aircraft parts could be produced faster and more accurately, while using fewer machine tools at a

significant cost savings. More versatile machine tools would reduce the number of machines necessary (for example, variable rpm rates would allow one spindle to cut both aluminum and steel parts).

### Consortium Plans to Develop Three Prototypes

The NCMS team had a preliminary spindle design and a development approach with the following three phases:

- Testing components
- Producing prototypes and performing general cutting tests
- Machining production parts

Consortium members would contribute their various specialties to the ATP-funded project:

- NCMS would provide organization and management.
- SETCO-Whitton (later renamed SETCO Sales Company), an independent spindle producer, would perform bench tests of all spindles.
- Giddings and Lewis and Olofsson Machine Tools Inc. (later renamed Olofsson, LLP), machine tool builders, would perform cutting-related tests.
- Manufacturing Laboratories Inc. and MagnaPhysics Corporation (later renamed Motorsoft, Inc.), a subcontractor, would build the motor.
- ORSCO would develop spindle lubrication.
- Ford Motor Company and General Motors Corporation would provide production components and testing.
- Torrington Company, a bearing manufacturer, would perform production validation tests.

In addition, research consultants Dr. Alexander Slocum from Aesop Inc. and Dr. Jiri Tlustý from the University of Florida would review designs, test prototypes, and interpret test results.

The NCMS team developed the following three basic prototypes:

- A spindle to allow high-speed milling of steel parts for a high metal-removal rate
- A spindle to meet flexible machining requirements

- A four-spindle cluster for simultaneous multiple-hole production in automobile transmissions and engines

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### Team Achieves Award-Winning Results

The NCMS consortium developed synergistic improvements to motors, bearings, and spindles. They applied these in the following three prototype tools:

- The heavy-duty 75-hp spindle (see Figure 1) offers high cutting accuracy at very high speeds (up to 60,000 rpm, which is 50-percent higher than conventional spindles) without overheating or losing power. It bores cylinders and mills flat surfaces at twice the removal rate of existing spindles. This motor uses roller bearings.

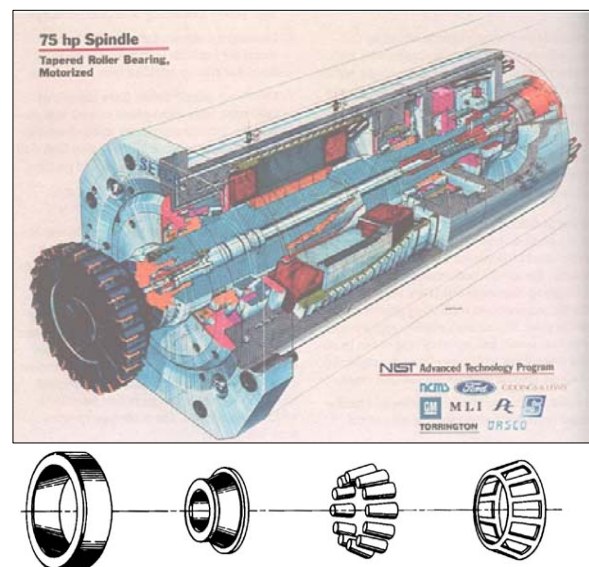


Figure 1. Top: Diagram of the prototype heavy-duty 75-hp spindle. The assembly measures approximately 25 cm in diameter and 64 cm in length. Bottom: Diagram of the tapered bearing designed for maximum load capacity.

- The high speed 35-hp spindle (see Figure 2) delivered accurate results at speeds from 2,500 to 20,000 rpm, which is useful for different types of metal. This spindle used hybrid ceramic ball bearings.

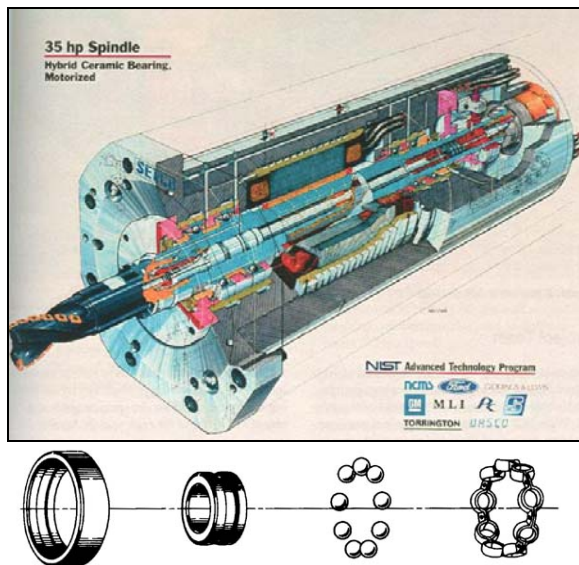


Figure 2. Top: Diagram of the prototype high-speed 35-hp spindle. The assembly measures approximately 25 cm in diameter and 69 cm in length. Bottom: Diagram of the ceramic ball bearings.

- A water-lubricated, self-compensating spindle cluster allows accurate clusters of four closely spaced holes (see Figures 3 and 4). The water-based coolant allows the spindle to be used at high production rates without overheating. This spindle has a larger shaft diameter, which provides greater stiffness and suppresses vibration. Self-compensating hydrostatic bearings formed on the tool shaft support the unit within the spindle housing. High-pressure coolant passes to the thrust bearing at the back of the tool. The fluid system reduces power consumption and heat generation, because water is less viscous than oil and has a higher heat capacity. The hydrostatic compensation system, called HydroSpindle, won an R&D 100 Award in 1996. A later development, TurboTool, built on the hydrostatic bearings and also won an R&D 100 award in 1997. This work was funded by NCMS, the National Science Foundation, and another machine tool builder.

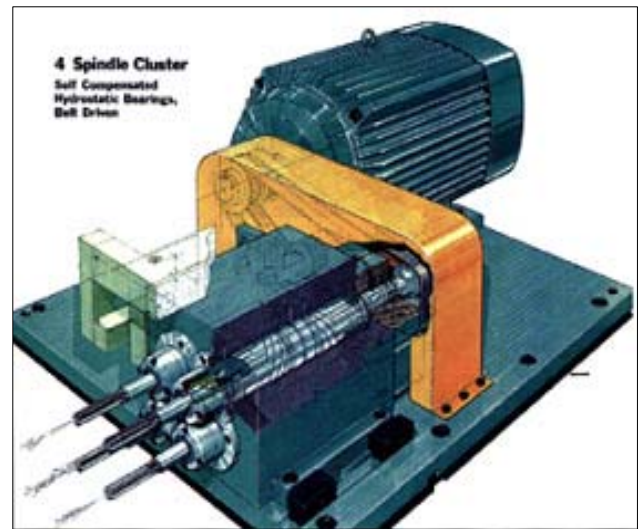


Figure 3. Top: Four-spindle cluster precisely drills four holes simultaneously. The spindle assembly measures approximately 44 cm in length (excluding the motor); the face plate measures approximately 25 cm x 20 cm. Bottom: Close-up view of the spindle housing with hydrostatic bearings. This award-winning prototype, called TurboTool, grew out of and matured from the ATP-funded technology, enabled by the hydrostatic bearings.

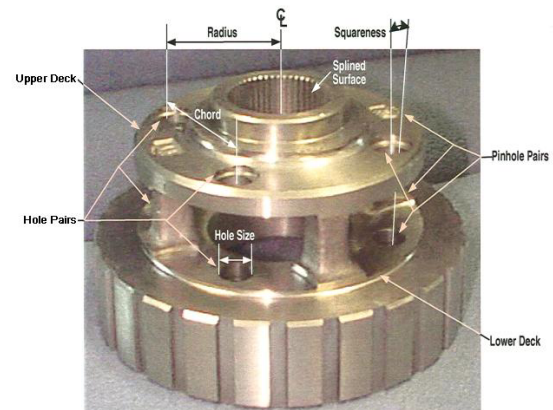


Figure 4. Sample automotive transmission part used to evaluate the four-spindle hydrostatic cluster's drilling ability. Note the four vertical hole pairs that were cut simultaneously. This previously required multiple passes through a spindle station, or the use of an earlier cluster spindle, which did not drill the holes accurately enough.

Two motor improvements contributed significantly to the prototypes' success: a motor-winding technique and a new, permanent-magnet motor design. The new, patented motor-winding technique, which won an R&D 100 Award in 1999, more effectively mitigates heat. Furthermore, it delivers 30 percent more torque to the cutting tool, equipped with a digital controller, so one spindle can cut both steel and aluminum for greater flexibility. The motor size was reduced by 50 percent and weight was reduced by 85 percent. The result was a compact, lightweight motor with high velocity. A phase advance in the drive system allowed high-speed torque to be available over an extended speed range.

The permanent-magnet motor design allowed a wider constant power range (for example, high torque and low speed for steel cutting and high speed and low torque for aluminum). It also facilitated a smaller sized motor with a larger diameter shaft and higher revolutions per minute for small spaces. By the end of the project, spindle speeds had reached 20,000 rpm, up from 3,600.

### Prototypes Are Put on Hold

The U.S. machine tool industry declined after the ATP-funded project ended in 1999. The machine tool industry had been hit hard by the transfer of manufacturing jobs overseas and by the downturn in the U.S. manufacturing economy. To reduce overhead, machine tool manufacturers were shifting to a global market, increasing outsourcing, and implementing efficient supply chain management (getting the right parts to the right customers at the right time).<sup>1</sup> Machine tool prices have been falling, while precision has been increasing, so manufacturers have little financial margin to finance innovative developments. Growth has been possible in small, niche markets, but overall, many jobs have been lost.

Although the cluster spindle prototypes were technically superior to any others on the market and made excellent parts, they were not commercialized, because the system of pumps and tanks used to supply fluid to the hydrostatic spindle was too conservatively designed and was deemed too costly and difficult to maintain.

The over design was good for research, so the exact size could be determined. However, before a just-enough design could be created, the downturn hit.

The NCMS consortium has not been able to make the necessary investments to reduce the size and cost of the innovative spindles to meet market needs. However, the technology did lead to three innovation awards and three patents, and consortium members presented their findings and published numerous articles describing the ATP-funded technology.

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*Using the ATP-funded technology, Motorsoft continued to increase revolutions per minute and built a Boeing jet generator that reached 40,000 rpm.*

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Hardinge built a prototype lathe spindle called the Concept 2000 machine, which they demonstrated at the International Manufacturing and Technology Show in 2000. They acquired the Aesop hydrostatic spindle technology in 2001. It was one of the highest speed lathe spindles ever built, but Hardinge has not yet brought the spindle to market.

Olofsson Machine Tools Inc., a machine tool builder, went out of business in 2002. Employees reopened it as a smaller refurbishing company the same year, named Olofsson LLP.

The global machine tool spindle market was more than \$1 billion in 2004; more than half of this relates to spindle maintenance and refurbishment, instead of manufacturing and sales.<sup>2</sup> Spindle technology provides opportunities for small, niche businesses to upgrade, repair, and maintain existing equipment.

In addition to advances in manufacturing small parts, the ATP-funded project led to advancements in motor design: a new motor-winding technique and permanent-magnet motor design have mitigated heat and allowed higher revolutions per minute. Using the ATP-funded technology, Motorsoft, a subcontractor, continued to increase revolutions per minute and built a Boeing jet

1. "Cutting through the Core Issues: International Cutting Tool Manufacturers Convene to Address Industry Trends." *American Machinist*. vol. 145, no. 9, pp. 78-84, September 2001.

2. Merlo, Mauro. "Trends in Machine Tool Spindle Design." *Fabricating & Metalworking Magazine Online*. <http://www.fandmmag.com/home.asp>, May 5, 2005.

generator that reached 40,000 rpm. Motorsoft's employment grew from 10 in 1994 to 23 in 2000; its business transformed from motor development to manufacturing. Fisher Electric Technologies purchased Motorsoft in 2004. By 2005, the company was building gas turbine engine that reached 226,000 rpm.

"The sad fact is that American manufacturers do not compete on a level playing field... To survive they will need everyone to exhibit true 'leadership in manufacturing,'" says John B. Byrd III, President of the Association for Manufacturing Technology.<sup>3</sup> Olofsson LLP, Hardinge, and Fisher Electric Technologies each are developing portions of the ATP-funded spindle technology. The three companies with a stake in the ATP-funded spindle technology are actively engaged in developing innovation.

### Conclusion

A National Center for Manufacturing Sciences (NCMS) consortium submitted a 1993 proposal to ATP to develop innovative spindles and motor designs for U.S. manufacturing. The consortium was composed of the following designers, manufacturers, and end users: NCMS, Ford Motor Company, General Motors Corporation, Aesop (which sold the technology to Hardinge), the Torrington Company (later purchased by Timken), SETCO-Whitnion (later renamed SETCO Sales Company), Olofsson Machine Tools Inc. (later Olofsson LLP), Manufacturing Laboratories Inc., ORSCO Inc., and Giddings and Lewis. The project achieved 100 percent of its technical goals in accuracy, speed, and flexibility with the following three completed products: a 75-horsepower (hp) spindle, a 35-hp spindle, and a cluster of four spindles for simultaneous drilling. The consortium earned three patents and three technical awards. Project researchers shared their findings through numerous presentations and publications. However, the manufacturing and machine tool industries experienced an economic decline after the project ended, and none of the spindles has yet been commercialized. The ATP-funded project did facilitate the development of high-speed motors that have higher revolutions per minute (rpm). When the project began, the standard spindle motors operated at 3,000 to 3,600 rpm. The new spindles reached 20,000

rpm. Since 1999, one subcontractor, Motorsoft, has built on the ATP-funded technology and has developed motors with 40,000 rpm for Boeing jets and up to 226,000 rpm for a gas turbine engine in 2005.

3. Byrd, III, John B. "Reader Reply: AMT Responds." *Industry Week*, November 8, 2005. <http://www.industryweek.com/ReadArticle.aspx?ArticleID=10989>

## PROJECT HIGHLIGHTS

### National Center for Manufacturing Sciences

**Project Title:** Advanced Spindles to Improve Manufacturing Productivity (Strategic Machine Tool Technologies: Spindles)

**Project:** To develop advanced technologies for machine tool spindles aimed at eliminating machining process steps and introducing flexible machines in place of fixed transfer lines to improve U.S. manufacturing productivity.

**Duration:** 7/1/1994 - 1/31/1999

**ATP Number:** 93-01-0244

#### Funding (in thousands):

ATP Final Cost	\$3,310	45.2%
Participant Final Cost	<u>4,008</u>	54.8%
Total	\$7,318	

**Accomplishments:** The National Center for Manufacturing Sciences (NCMS) consortium met all their technical goals. They completed three prototype spindles that outperformed conventional spindles, in addition to a new motor-winding technique and a permanent-magnet motor design:

- The heavy-duty spindle has a 75-horsepower (hp) motor. It bores cylinders and mills flat surfaces at twice the removal rate of existing spindles.
- The 35-hp HydroSpindle delivered accurate results at speeds from 2,500 to 20,000 revolutions per minute (rpm), which is useful for cutting and milling different types of metal, such as aluminum and steel, without changing tools.
- A water-lubricated, self-compensating spindle cluster allows the drilling of four closely spaced holes instead of drilling through multiple passes.
- A new motor-winding technique mitigates the heat and provides a new digital controller. It delivers 30-percent more torque to the cutting tool, allowing one spindle to cut both steel and aluminum for greater flexibility.
- A new permanent-magnet motor design has facilitated rpm increases from 3,600 at project start to 20,000 at project completion. A subcontractor, Motorsoft, continued development after the ATP-funded project ended. They built a generator for Boeing jets that reached 40,000 rpm, and, in 2005, they were building a motor for a gas turbine engine that would reach 226,000 rpm.

Consortium member Aesop was awarded three patents for direct and indirect innovations associated with the ATP-funded technology:

- "Integrated shaft self-compensating hydrostatic bearing"  
(No. 5,700,092: filed August 23, 1995; granted December 23, 1997)
- "Method of winding motors and other electric machines to reduce AC losses"  
(No. 6,758,430: filed February 16, 1999; granted July 6, 2004)
- "Method of winding motors and other electric machines to reduce AC losses"  
(No. 6,455,971: filed January 25, 2000; granted September 24, 2002)

The NCMS team received three awards for this ATP-funded technology:

- R&D 100 Award from R&D Magazine in 1996 for the HydroSpindle bearing, a self-compensating, water-hydrostatic, fluid-film bearing that uses hydraulic fluid-resistance circuitry on the cutting-tool shaft.
- R&D 100 Award in 1997 for the TurboTool Ultra-High Speed Spindle, a spindle design that integrates the cutter, toolholder, spindle, and drive into a lightweight package and allows high power (100 kilowatts) and high-speed machining (100,000 rpm). This technology was a later development enabled by the ATP-funded hydrostatic bearings.
- R&D 100 Award in 1999 for the Motor Winding Method for Low Proximity Losses, which provides a new winding-pattern methodology to eliminate power loss when operating at 60 Hertz (cycles per second) or higher.

**Commercialization Status:** Motorsoft produced more than 10 engine models for sale based on the ATP-funded permanent-magnet motors. As a result of this commercial success, Fisher Electric Technologies acquired Motorsoft in 2004.

## PROJECT HIGHLIGHTS

### National Center for Manufacturing Sciences

**Outlook:** The outlook for the ATP-funded motor and spindle technologies is good but clouded. Fisher is prepared to commercialize high-speed motors as a small, niche manufacturer. The spindle technologies have some commercialization with respect to motor design, and they have won patents and innovation awards. Although U.S. manufacturing output is strong, and manufacturing productivity growth exceeds expectations, manufacturers face serious global competitive challenges. Hardinge and Fisher Electric Technologies each are developing portions of the ATP-funded spindle and motor technologies.

**Composite Performance Score:** \* \* \*

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#### Subcontractor:

- Fisher Electric Technology (formerly MagnaPhysics Corporation)  
Lebanon, OH

## PROJECT HIGHLIGHTS

### National Center for Manufacturing Sciences

**Publications:** The NCMS spindle technology gained public attention through the following publications:

- Tlusty, J., S. Smith, and R. Winfough. "Techniques for the Use of Long Slender End Mills in High Speed Milling." *Annals of the CIRP*. vol. 45, no. 1, 1996.
- "Building a Better Bearing." *Mechanical Engineering*. 118, 5, pp. 56-60, May 1996.
- Chung, B., S. Smith, and J. Tlusty. "Active Damping of Structural Modes in High Speed Machine Tools." *ASME J. of Vib. and Control*. 3, 1997.
- "High Velocity at Dearborn Engine." *Manufacturing Engineering*. May 1997.
- "Mill Spindle Driven by Water." *R&D*. 39, 10, p. 47, September 1997.
- "Five Best Bets: Five Research Projects Are Shaping the Future of Machine-Tool Technology." *American Machinist*. March 1998.
- "Spindles for 2000 and Beyond." *Manufacturing Engineering*. July 1998.
- "Tooling Trends." *Cutting Tool Engineering*. August 1998.
- Smith, D., S. Smith, and J. Tlusty. "High Performance Milling Torque Sensor." *ASME J. Mfg. Sc. and Eng.* vol. 120, August 1998.
- "Improved Spindles Cut More Materials at Lower Costs." *Advanced Manufacturing Technology Alert*. John Wiley and Sons, September 1998.
- "Stimulating High-Risk, High-Payoff Research." *The Industrial Physicist*. February 1999.
- "Strategic Machine Tool Technologies: Spindles, Final Report." *National Center for Manufacturing Sciences*. August 1999.
- "Motor Winding Method Cuts Power Losses." *R&D*. 41, 10, p. 109, September 1999.
- "Editors Awards." *R&D*. 41, 11, p. 51, October 1999.
- Kotilainen, M. S., and A. H. Slocum. "Manufacturing of Cast Monolithic Hydrostatic Journal Bearings." *Precision Engineering*. 25, pp. 235-244, 2001.
- "An Evaluation of the Design and Performance of Three Advanced Spindles." *National Center for Manufacturing Sciences*. June 2001.
- Slocum, A. H., M. Basaran, R. Cortesi, and S. Nayfeh. "Get a Preload of This: Actuator/Bearing Technology Is Changing How Grinding Machines Move." *American Machinist*. p. 48-51, December 2002.
- Kane, N. R., J. Sihler, and A. H. Slocum. "A Hydrostatic Rotary Bearing with Angled Surface Self-Compensation." *Precision Engineering*. 27, pp. 125-139, 2003.
- Slocum, A., M. Basaran, R. Cortesi, and A. J. Hart. "Linear Motion Carriage with Aerostatic Bearings Preloaded by Inclined Iron Core Linear Electric Motor." *Precision Engineering*. 27, pp. 382-394, 2003.
- Sharke, P. "Back to Motor School." *Mechanical Engineering*. vol. 125, no. 12, pp. 28-32, December 2003.

### Presentations:

- Wasson, K. International Machining and Grinding Conference, Society of Manufacturing Engineers, Detroit, MI, September 1997.
- Grant, J. W., and J. T. McCabe. "Compact, High-Power Spindles." National Institute of Standards and Technology (NIST) ATP Motor Vehicle Manufacturing Technology (MVMT) public workshop, Gaithersburg, MD, October 1997.
- Schaffa, R., J. T. McCabe, and K. Wasson. "Advanced Hydrostatic Bearings for a New Class of Machining Spindles." NIST ATP MVMT public workshop, Gaithersburg, MD, October 1997.
- Tlusty, J., S. Smith, S. J. Badrawy, D. Smith, and A. Smith. "Design of a High Speed Milling Machine for Aluminum Aircraft Parts." ASME 1997 International Mechanical Engineering Congress, Dallas, TX, November 1997.
- Tlusty, J., J. C. Ziegert, and S. Ridgeway. "Stiffness of Structures and Drives in Fast Milling Machines." SAE Aerospace Manufacturing Technology Conference, Seattle, WA, June 1999.